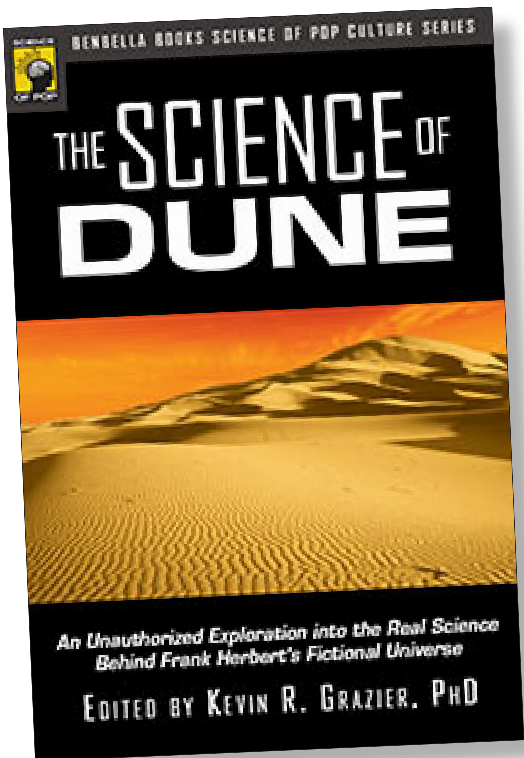
This essay is from

THE SCIENCE OF DUNE



We've chosen to make our direct sale e-books DRM-free.

That means you can upload this PDF to any digital reader or read it on your laptop or desktop computer. It also means you're free to share this book with a friend the same way you would a physical book. We just ask that you not upload the file anywhere for others to download.

Thanks, and enjoy!

THE SHADE OF ULIET: MUSINGS ON THE ECOLOGY OF *DUNE*

David M. Lawrence

Arrakis. Dune. Desert planet. Arrakis has in abundance: sand, sand dunes, sand storms, sandworms, and sandtrout. It's easy to suppose that the ecology of a world like Arrakis would be fairly . . . parochial . . . in its scope. Scientist and journalist David M. Lawrence reveals that it is anything but.

> The human question is not how many can possibly survive within the system, but what kind of existence is possible for those who do survive.
>
> —Pardot Kynes

IF THE WAY BIOLOGISTS used to whisper about Frank Herbert's *Dune* is any indication, it was held in as high regard as the music of Thelonius Monk is held among jazz fanatics. They spoke of it in low, knowing whispers, nodding and waving their hands in a fashion that made one want to read the book in order to become as cool as they were.

Well, as cool as one biologist could look to another.

I first heard of *Dune* nearly thirty years ago, while an undergraduate at Louisiana State University in Shreveport. One of my mentors, a botany professor named Steve Lynch, repeatedly praised *Dune* as a work of ecological enlightenment. Reading the book, he said, was a life-changing experience.

Coming from Steve that said a lot. To a boy who grew up in northwestern Louisiana, Steve had the right credentials to know "cool." He was from California. He wore shorts and flip-flops to class. He played

guitar. He may or may not have inhaled. His golden Labrador retriever, Cooper, was smarter than many of my fellow students—and better company. And Steve was active in environmental causes.

He said I should read the book.

I filed away the suggestion, but beer, sex, and ZZ Top (not necessarily in that order) kept me too preoccupied to act for years. Nevertheless, I managed to catch every mention of it, no matter how far away, no matter how faint—like a radio telescope picking up transmissions of the value of π [pi] from somewhere in a galaxy billions of light years away. Still, I did not read the book. I paid great attention to the release of the movie, and did not see it—I wanted to read the book first.

But I did not, until recently.

The bulk of *Dune* is set on Arrakis, also known as Dune, a desert planet covered in massive sand seas with occasional rock-lined canyons, escarpments, and pavements. Hot, dry weather is broken up by vicious sand storms. Gigantic, hungry worms stalk the sands, preying on (or defending themselves against) inexperienced travelers that dare intrude upon the worms' domain. Arrakis is populated by one race of humans: ancient migrants, now long established and virtually native, that thrive in the wastes, expertly conserving the planet's most precious resource—water. These people are known as the Fremen.

Arrakis—the sole source of melange, or spice (the substance said to give its users prophetic powers), has important similarities to Earth. Like Earth, it is the third planet in its solar system. The Arrakean atmosphere is 75.4 percent nitrogen, 23 percent oxygen, 0.023 percent carbon dioxide, and trace gases; Earth's atmosphere is 78.1 percent nitrogen, 21 percent oxygen, 0.93 percent argon, 0.037 percent carbon dioxide, and trace gases. The chemistry of the Arrakean system is similar to that of Earth. The life is carbon-based. By inference, the availability of chemical building blocks for organic molecules is similar. In fact, as explained in the appendix to the first novel (*The Ecology of Dune*), plant growth is limited by the availability of trace minerals—fixed (organic) nitrogen and sulfur, in particular—much as plant growth on Earth is limited by availability of such minerals.

Nevertheless, the most limiting chemical constituent on Arrakis is water.

The portion of Arrakis most suitable for terraformation occured in a wide latitudinal belt ranging between 70 degrees north and 70 degrees south. On Earth, the most habitable portion occurs in a similar latitudinal band (roughly between 67 degrees north to 67 degrees south), with the boundaries determined largely by the location of the north and south polar fronts. As on Earth, the highest temperatures on Arrakis are found near the equator while the lowest are at the poles. The average temperatures on the Dune planet, however, are about the same as Earth, too. The average temperature at the Earth's surface is about 287 degrees K (what is referred to in *Dune* as absolute), or 14 degrees C (57 degrees F), whereas average temperatures in Earth's polar regions (beyond 66.5 degrees north or south latitude) range from near to well below freezing (less than 273 degrees K, 0 degrees C, or 32 degrees F).

Temperatures in the Arrakean polar regions are similar to that of Earth, ranging from near to well below freezing, thus permitting the existence of small icecaps that will potentially serve as important reservoirs of water. Between Dune's polar regions, however, temperatures range from 254 degrees to 332 degrees K, which is equivalent to a range of -19 degrees C to 59 degrees C or -2 degrees F to 138 degrees F. The tropical and middle latitudes of Arrakis have long growing seasons with temperatures in the 284 degrees to 302 degrees Kelvin range (11 degrees C to 29 degrees C or 51 degrees F to 84 degrees F), similar to that characteristic of the most productive terrestrial ecosystems of Earth.

Readers of science fiction and fantasy are expected to suspend disbelief. Disbelief is required when Herbert described the massive sandstorms that raged across the surface of Arrakis. One of the factors he said that contributed to the strength of the storms was the Coriolis effect. The effect, since it is often referred to as a "force," may seem a logical factor to consider in the strengthening of storm winds on the basis of the name. The Coriolis effect is not a true force, however. It adds nothing to wind speed. It is an apparent deflection in the path of a moving object, such as a storm system, when plotted on a rotating frame of reference. The object may actually move in a straight line, but it appears to follow a curved path as the frame of reference rotates out from under it.

For example, you and a friend are on opposite sides of a spinning merry-go-round. You are inspired to bean your friend with a tennis ball and throw it straight at him. You miss! The problem was not your aim. The problem was not the ball; it traveled in a straight line. The problem was that, as the merry-go-round spun, it carried your friend out of harm's way. If someone viewing the mayhem from a tower above plotted the path of the ball *on the merry-go-round*, the path would appear to be curved. On Earth, objects in the Northern Hemisphere appear to be deflected to the right. In the Southern Hemisphere, they appear to turn to the left. The spiral motion of winds around the eye of a hurricane is a product of the Coriolis effect. The speed of the winds around that eye is not. Wind speeds result primarily from the air pressure gradient as one moves from the eye outward. The steeper the pressure gradient (i.e., the greater the difference in pressure), the faster the wind speeds.

Herbert's description of the role of sandworms in the maintaining the oxygen concentration of the Arrakean atmosphere likewise requires substantial disbelief. The most widespread ecosystem on Arrakis is the desert. The sands of the desert are in part maintained and conditioned by the sandworms themselves. This is similar to the role of earthworms in your garden. The sandworms play a role in the generation of melange, which tiny sand plankton feed on, and sandworms in turn feed on the sand plankton. Herbert proposed a simple nutrient cycle, although it is more similar to that of the Earth's oceans than of any terrestrial ecosystem. The plankton are the producers, the sandworms are consumers (and somewhat omnivorous ones, too, as they feed on the sand plankton as well as on themselves). The sandworms, whether by their role in the production of melange, their own wastes, or the recycling of material from their own decomposition, produce nutrients for the plankton. With respect to nutrient cycling, so far, so good. The problem is in the cycling of oxygen. On Earth, the producers, typically photosynthetic plants and cyanobacteria, produce oxygen as a byproduct of the reaction that produces sugar from carbon dioxide and water. On Arrakis, the ultimate consumer, the sandworm, is responsible for oxygen production. An organism that can grow to as much as 400 meters long and travel through sand at speeds many fish can't achieve in water on Earth would seemingly consume a sub-

stantial amount of oxygen. That such an organism would become a net producer of oxygen seems implausible. Herbert wrote *Dune* more than a decade before the discovery of deep-sea ecosystems that are not based on photosynthesis, and therefore do not depend on the sun for survival. Had he known of such ecosystems, he might have devised a more credible explanation of the Arrakean oxygen cycle.

Unlike Earth, which is covered mostly by the oceans, Arrakis lacks much surface water. The desert planet is much more like Mars, with evidence of flowing water at some point in the distant past. While in the frigid temperatures of Mars, the evidence of surface water comes from the existence of fluvial landforms like gullies and canyons that on Earth are created by flowing water. In the case of torrid Arrakis, the salt pan discovered by Pardot Kynes, who was appointed by the Padishah Emperor Elrood IX as the first planetologist of Arrakis, is likewise evidence of water that had once been on the surface. Salt is not a product of volcanism. It is not a component typically found mixed with lava, for example. On Earth, salt is typically dissolved in water. Most is in the oceans, but some is in fresh water. When it is found in large deposits on land, such as in salt pans or salt domes, it is because the salt was left behind by water that at some point had evaporated away from the site.

What little surface water that existed by the time that Kynes arrived on Arrakis was found frozen in the tiny polar ice caps. The landscape is harsh, deadly for all but the hardiest, savviest inhabitants. Kynes sought to make the planet more livable for its human inhabitants. The desert conditions on Arrakis pose a seemingly insurmountable challenge: water is essential for life.

Despite the lack of water at the surface, Kynes discovered (before the events related in *Dune* take place) liquid water in the ground, and water vapor in the atmosphere above. He devised a plan to harness water and terraform the planet. Increased water at the surface will enable the establishment of a more and more diverse assemblage of species, ultimately leading to functioning ecosystems capable of sustaining themselves.

Because the Harkonnen overlords of Arrakis cared little about the livability of the planet (their priority is the production of melange), the elder Kynes launched the plan in secret, enlisting the Fremen, who

longed for freedom from Harkonnen oppression. As he demonstrated himself to be a willing and efficient killer of the hated Harkonnen, the Fremen chose to follow Kynes. Their bond was cemented through his marriage to a Fremen woman and fathering Liet-Kynes. The younger Kynes fulfilled all the rites of passage expected of Fremen males and was fully accepted by Fremen society. In fact, both the elder and younger Kynes became semi-mystical leaders of the Fremen.

Herbert's keen grasp of ecology is evident in his description of the elder Kynes's plans of how to terraform the Arrakean landscape. The transformation began with the construction of wind traps to intercept water vapor from the air and underground basins to store the collected water. With sand surface temperatures ranging from 344 degrees to 350 degrees Kelvin (71 degrees C to 77 degrees C or 159 degrees F to 170 degrees F) and with hot air temperatures (46 to 52 degrees C or 114 to 125 degrees F) above, one can expect ready loss of surface water to the atmosphere through evaporation unless there is some way to shield the water supply from the heat. Then the greening of Arrakis began. Water-efficient species that also served as excellent ground cover were planted first. As the dunes were stabilized with the plant cover protecting the dune surface from wind erosion, weedy species were planted next, followed by low perennials, and then larger perennials: cactuses, shrubs and trees tolerant of arid conditions. The ultimate goal was to cultivate food and medicinal species.

The elder Kynes's plan had a logical progression. Each cohort of plants will help stabilize the sand surface, capture more water from the atmosphere and retain it in the biomass and ground, and transform the mostly mineral sand into true soil by enriching it with organic matter and nutrients. The success of one cohort will make the changed environment suitable for subsequent plantings. Kynes recognized that plants cannot succeed on their own. They needed animals, both invertebrates and vertebrates, to help work the soil, contribute to nutrient cycling, pollinate flowers, and graze to prevent fecund and fast-growing species from the others.

The elder Kynes recognized one other important fact: his plan would fail unless it was sustained over the centuries. As the Fremen were his only hope for carrying out the plan, he had to educate them in ecological matters. His educational program skillfully exploited their re-

ligious beliefs, binding his ecological principles with their traditional ethical and moral principles to create an environmentally enlightened society. He groomed his son as his successor. A wise move, as he was killed prematurely in a cave-in at the Plaster Basin. His son, appointed his successor as planetologist of Arrakis by Padishah Emperor Shaddam IV, was continuing his terraforming program at the time Duke Leto Atreides assumed the fiefdom of the planet at the behest of the Padishah Emperor.

> The effect of Arrakis on the mind of the newcomer usually is that of overpowering barren land. The stranger might think nothing could live or grow in the open here, that this was the true wasteland that had never been fertile and never would be.
>
> —From *The Ecology of Dune*

The elder Kynes's plan may seem far-fetched—terraforming a planet—but humans have terraformed landscapes for millennia. Unless one includes an unproven (though not far-fetched) hypothesis that pre-agricultural humans opened up the landscape to make it more suitable for hunting by harnessing fire, the first major transformation of the landscape was the transformation of steppes and forests into farmland at the dawn of civilization. Irrigation and cultivation are hallmarks of human settlement in arid regions. The kind of transformation Herbert envisions in *Dune* is far grander and much more fundamental than anything attempted on Earth.

Or is it?

In March of 2007 I joined a biological expedition to Ascension Island, the peak of a volcano rising from the mid-Atlantic Ridge in the South Atlantic Ocean. It is small, only about ninety square kilometers (thirty-six square miles), with its highest point about 860 meters (2,817 feet) above sea level. It is not a classic desert island, i.e., not the kind of place envisioned by people "informed" by the writings of Robert Louis Stevenson, such as *Treasure Island*, or movies like *Pirates of the Caribbean*. It is not a choice destination for people whose ideas of roughing it consist of sun, sand, and bizarre alcoholic concoctions topped by miniature umbrellas. Given that Ascension is home to both British and American military installations, thus populated by mili-

tary personnel and contract workers, and given that there are few recreational opportunities (there is only so far one can drive), I am sure one can find plenty of bizarre alcoholic concoctions. There is no shortage of sun and sand. There also is, unlike Arrakis, plenty of water. The nearest land is Napoleon's final home of St. Helena and is about 1,200 kilometers (750 miles) away. But the ocean water is of no use for drinking (without desalinization) or irrigation. Ascension is located near the equator, thus hot with few breaks in the weather. There are none of what most people outside the tropics call seasons.

Charles Robert Darwin visited Ascension in 1836, near the end of the expedition that provided the seed for what became his theory of evolution by natural selection. He aptly describes Ascension in his memoir, *Voyage of the Beagle*:

> On the 19th of July we reached Ascension. Those who have beheld a volcanic island, situated under an arid climate, will at once be able to picture to themselves the appearance of Ascension. They will imagine smooth conical hills of a bright red colour, with their summits generally truncated, rising separately out of a level surface of black rugged lava. A principal mound in the centre of the island, seems the father of the lesser cones. It is called Green Hill: its name being taken from the faintest tinge of that colour, which at this time of the year is barely perceptible from the anchorage. To complete the desolate scene, the black rocks on the coast are lashed by a wild and turbulent sea. . . .
>
> Near this coast nothing grows; further inland, an occasional green castor-oil plant, and a few grasshoppers, true friends of the desert, may be met with. Some grass is scattered over the surface of the central elevated region. . . .

Joseph Dalton Hooker, a friend of Darwin's who was one of the leading botanists, as well as one of more eloquent advocates for the theory of evolution, also visited Ascension in 1843 while accompanying James Clark Ross's expedition to Antarctica. In an 1866 article entitled "Insular Floras," Hooker wrote that the island "consists of a scorched mass of volcanic matter, in part resembling bottle glass, and in part coke and cinders. A small green peak, 2880 feet above the sea, monopolises nearly all the vegetation, which consists of purslane, a grass, and a euphorbia in the lower parts of the island, whilst the green peak is

clothed with a carpet of ferns and here and there a shrub allied to but different from any St. Helena one." Probably only about three dozen plant species could be found on Ascension at the time of its discovery. With the exception of seabirds, a flightless rail, and sea turtles, the largest animals native to Ascension were land crabs and insects.

Further confirmation of Ascension's desolation is in the fact that the Portuguese, who discovered the island in 1501, uncharacteristically deemed it unworthy of colonization. The British finally settled the island in 1815 for strategic reasons alone. After Napoleon's exile to St. Helena, they did not want the French to use the island as a base from which to liberate the conquered emperor. Once there, the British decided to keep a garrison on the island, but struggled to make it habitable. Hooker, after the Ross expedition, devised a plan to achieve that goal, thus becoming the Pardot Kynes of Ascension history.

In 1847 Hooker prepared a report for the British Admiralty outlining a program of terraforming (long before the term was coined) Ascension. As with the elder Kynes's plan for Arrakis, it was multifaceted. Hooker suggested that rainfall on the island could be increased by planting large trees on the upper slopes of Green Mountain (Darwin's Green Hill). Steep ravines should be planted with shrubs, low trees, and cactuses. He felt these woody species would promote soil formation and reduce evaporation of moisture from the soil surface. Valleys at lower elevations should be planted with appropriate species, such as acacia, casuarina, eucalyptus, and other plants adapted to arid conditions. Finally, tropical and European crops should be planted in gardens high on Green Mountain. Hooker recommended some species that could be introduced and outlined where those species could be obtained. (Many were supplied by the Royal Botanic Gardens at Kew, to which Hooker succeeded his father, William Jackson Hooker, as director.) Plants had been imported haphazardly prior to Hooker's report. Even less planning was devoted to animal introductions. Some imports, such as rats and mice, were desired by no one. Hooker's report provided a sense of purpose and organization to the effort to transform Ascension.

The Royal Navy and Marines followed the recommendations of Hooker, employing a succession of gardeners to carry out the planting program. The first two gardeners did their best, but life on the

island proved too much and they (or in one case, a wife) helped engineer pretexts to get them returned home to England. While their efforts to make the bare slopes of the cinder cones “productive” as the Royal Navy requested failed, Green Mountain was slowly transformed. The transformation flourished under the guidance of the third gardener, a civilian named John Bell. Under his regime agricultural production from the gardens on Green Mountain increased by 50 percent to 90,000 pounds. He planted tens of thousands of trees and shrubs.

Plants were brought in from all parts of the world: Buddleia, chasteberry, greasy grass, and periwinkle from Africa; acacia, agave, aloe, and prickly pear cactus from the Americas; bamboo, banyan, and ginger from Asia; blackberry and raspberry from Europe; casuarina and eucalyptus from Australia; and screw pine and coffee wood with worldwide or nearly worldwide distributions. Animals introduced to Ascension included cats, donkeys, goats, sheep, and a number of birds, including, for example, the Indian mynah.

By the time I arrived at Ascension, the summit of Green Mountain had been transformed from a rocky prominence with a faint green cap of ferns to a diverse, artificial—yet functional—forest. A thick stand of bamboo blankets the highest elevations. Surrounding the bamboo, especially on the northern slopes of the peak, is a forest consisting of tall specimens of eucalyptus, mulberry, palm, screw pine, yew, and others. The cloud forest at the summit grades into expanses of grass and scrub forest at lower elevations. Greasy grass and guava are common on drier slopes. Bermuda cedar and casuarina create something of a forest in more humid locations. A spectacular grove of Norfolk Island pine occurs on the southeast slope. At lower elevations, wide expanses of a stark, charred volcanic landscape prevail. Indigenous plant species can be found in gullies fed by occasional heavy rains, but a number of introduced species have gained a toehold there as well, including castor oil, horse tamarind, waltheria, and the yellow thistle. Prior to the establishment of the British garrison, the lower elevations outside the gullies were bare except for brief periods after heavy rains when pappusgrass flourished. Now, mesquite (called Mexican thorn on Ascension) and prickly pear, staples of American deserts, have spread and are helping transform bare volcanic rock in to true soil.

While the introduction of many plants to Ascension followed some-

thing of a plan—Hooker's—the introduction of animals to the island had a far more haphazard history. Rats (both black and Norway) and house mice were accidentally introduced from ships (it should be no surprise that no one wanted them, either at sea or on shore). Goats were probably brought to the island shortly after its discovery as a source of food for meat-starved sailors (this was common practice in the age of sail). With the British attempt to launch agriculture in the nineteenth century came agricultural pests. Birds (starlings, thrushes, rooks, jackdaws, common waxbills, yellow canaries, and the Indian mynah) were introduced to help control insects. Hedgehogs were also brought in to control agricultural pests. Cats were released in the hopes that they would help control rats, as were barn owls. Rabbits were imported as game. Cattle and sheep arrived with the British garrison in its attempt to establish agriculture. Donkeys were brought in as beasts of burden.

The introductions have a mixed record. Some of Hooker's vision has been borne out—especially by the transformation of the summit of Green Mountain into cloud forest. Whether or not the forest has led to increased rainfall is arguable, but the vegetation serves moisture captured from the southeast trade winds, keeping the summit enshrouded in clouds. (Ironically, the development of the forest may have contributed to the drying of springs on the slopes of Green Mountain, as water that used to bubble out of the ground is now pumped into the atmosphere through transpiration, loss of water through stomates, or openings, in the leaves of the plants.) Hooker's plan has likewise worked for the lower elevations as species like mesquite and prickly pear build soil on what was once a barren, ash- and rock-covered surface. These plants are often candidates for control by Ascension conservation authorities. The downside of this transformation has been the extinction of some endemic species: plants that were known only to Ascension. Other endemic species have been reduced in number, or their ranges on the island have gotten smaller and smaller as a result of competition with introduced plants.

Introduced plants had an easier time of it on Ascension than introduced animals. A number of the bird species introduced during the nineteenth century failed to gain a toehold on the island. Only the canary, francolin, mynah, and waxbill had successfully established them-

selves. Another import, the house sparrow, has gained a toehold on the island in the twentieth century, primarily in developed portions of the island.

The larger animals such as goats, sheep, cattle, and donkeys have significantly influenced the plant community, helping to expand the range of introduced plant species on Ascension at the expense of natives. While goats were eliminated by the middle of the twentieth century, and cattle were nowhere to be seen during my expedition in 2007 (although one is reported to survive on Green Mountain), donkeys and sheep are still quite common. In recent decades both have contributed to the rapid spread of mesquite, a recent introduction to the island. Introduced animals, primarily rats and the cats brought in to control them, have often had a devastating effect on native animals, particularly seabirds and sea turtles that breed there, by preying on the nests, eating eggs and hatchlings. The flightless Ascension rail was probably rendered extinct by predation from rats before the British garrisoned the island in 1815. The combined pressure by cats and rats has driven many seabirds from their roosting areas on the island, but the recent elimination of feral cats has allowed some of those species to return.

As with Kynes's plans for Arrakis, the reason for terraforming Ascension was to make the island more livable. A primary goal was to increase the available water supply, and one way to do that is to capture moisture available from the atmosphere. As on Arrakis, the amount of water available in the air on Ascension increases with elevation, especially on the southern and eastern slopes of Green Mountain, which are exposed to the southeast trade winds. Thus, the British garrison constructed its own version of a water collector. They paved the head of Breakneck Valley, a long, southeast-facing valley that runs from the summit of Green Mountain to its base, and installed a collection basin and piping at the lower portion of the pavement to gather and transport water to the island's settlements.

As the history of Ascension Island bears out, terraforming even a relatively small landscape is difficult. It is difficult to consider the magnitude of the task the elder Kynes set for himself and the Fremen—to embark on a three- to five-century-long project to terraform an entire planet—without a shudder. The large area to be transformed, the

harsh initial conditions, and the dearth of raw materials make success unlikely. The consequences of failure were high: too much water could poison the sandworms, thus destroying melange production as well as a major source of oxygen for the planet's inhabitants. But Kynes embarked on the project with a faith that justified his status as a holy man among the Fremen.

As with Hooker's recommendations for Ascension, the elder Kynes's plans for Arrakis drew upon a diverse pool of plant and animal resources for transformation of Ascension. The process begins with the planting of poverty grasses, which in their native North America grow on sandy, impoverished soils (such as coastal dunes). Through their extensive root systems these plants bind the sand grains and make the soils less susceptible to erosion by wind or water. Once the poverty grasses have minimized the wind erosion, hence migration, of the Arrakean sand dunes, sword grasses (a term that refers to a widespread but taxonomically diverse array of species on Earth) will be used to further stabilize the dunes.

Once the physical stabilization of the dunes is achieved, the next task is the transformation of the mostly mineral sand to more organically enriched (thus more fertile) soil. Kynes started that with an array of ephemeral (weedy) species, such as pigweeds, a collective term that includes both *Amaranthus* and *Chenopodium*. As weeds, they can grow on infertile sites. As such species germinate, grow, reproduce, and die, they chemically alter the soil around them via reactions in the root zone as well as by adding organic matter through decomposition.

The next phalanx of plants to be planted by Kynes included scotch broom, low lupine, dwarf tamarisk, and shore pine as well as the classic desert species: barrel cactuses, candelilla, and saguaro. Scotch broom, which is native to Europe and Africa, and low lupine, native to North America, are legumes. As such, they, with the help of nitrogen-fixing bacteria in their roots, naturally fertilize the soil with organic nitrogen that can be taken up by other species. Dwarf tamarisk, a native of arid lands in Africa and Eurasia, and shore pine, native to North America, are both tree species that do well on dry, nutrient-poor soils. Cactuses are native to the Americas, commonly found in desert regions. Both barrel cactuses and saguaro are succulents, e.g., they store water in their stems. (Saguaro is the giant of the America deserts, growing to

more than 13 meters [forty-two feet] tall.) Cactuses have green stems and lack leaves. This allows them to make their own food (sugars) via transpiration while minimizing the loss of water via transpiration. Candelilla, while native to North America, is a member of the spurge family, whose species often play a similar role in Eurasian and African deserts as the cactus family does in the Americas. Succulent spurges even look like cactuses, with green stems and reduced or no leaves to allow photosynthesis while limiting water loss.

In suitable areas, Kynes recommended the planting of other species, all of which can be found on Earth in arid and semi-arid environments. These included onion grasses, which have a widespread distribution; Gobi feather grass, from the steppes of Eurasia and Africa; camel sage, a perennial herb found in Eurasia and Africa which is known for its sand-stabilizing abilities; evening primrose, found in dry and disturbed environments of North America; sand verbena, a creeping plant from the deserts and other sandy environments of the Americas; wild alfalfa, a legume native to grasslands and woodlands of North America; the burrow and creosote bushes, shrubs in desert North America; and incense bush, a name that refers to a number of unrelated shrub in both of the Americas.

Kynes knew that a functional ecosystem consisted of more than just plants, so he introduced animals as well. Just as the plants, the candidates for animal introductions were selected with a specific purpose in mind. Herbivores, for example, keep the plant population in check in a functioning ecosystem. Without them, some plant species would overgrow the others. Carnivores keep the herbivore population under control. Without predators, the herbivores would increase in numbers and overgraze the vegetation. Kynes first selected burrowing animals to work the soil: the kangaroo mouse, an herbivore, the kit fox, a carnivore, both natives of North America, and the sand terrapin, an herbivore, possibly the desert terrapin of the southwestern United States. Another herbivore, the desert hare, could either be a Eurasian species or else a species also known as the black-tailed jackrabbit of North America. He chose other vertebrate predators to help manage the herbivore population: desert, dwarf, and eagle owls, and desert hawks (each with a number of possible Earth analogs). Kynes did not ignore the invertebrate world, adding familiar residents of arid environments:

the biting wasp, centipede, scorpion, trapdoor spider, and wormfly, and adding desert bats to control the invertebrates (although it is unlikely that bats would normally prey on most of the invertebrates mentioned).

Once the transformed Arrakean ecosystem proved it could function, Kynes planned to introduce food crops such as date palms and melons, coffee, fiber crops such as cotton, and medicinal plants.

In the Dune universe, the elder Kynes's plan succeeded so well that 200 years after Paul Atreides, son and heir of Duke Leto Atreides, defeated the Imperial and Harkonnen forces that conspired to kill his father (and who also murdered Liet-Kynes by abandoning him in the desert), the waters that once covered the surface of Arrakis returned and drove the sandworms and sandtrout (a larval form of sandworm) to extinction.

Kynes's plan was carefully thought out, tested, revised, and tested again. Terraforming does not have to proceed in such a logical fashion to work, however. Hooker had a plan for Ascension Island, but much of the terraforming work was done by accident, without thinking. Mistakes were made, as in the devastating effect that cats brought in to control rats had on the native bird life. But parts of the effort worked better than expected.

Under normal conditions, ecosystems are assembled over time in a process called succession. In the case of relatively bare land, succession typically begins with a few fast-growing species that modify the environment, such as adding nutrients to the soil and making conditions favorable to other species. The later arrivals continue to modify the environment, and new species colonize the system until a point where the amount of living matter and often the diversity of the system are maximized. Species that fit in with others present become successfully established. Those that don't cannot gain a toehold and fail. In many ecosystems, this process takes centuries. (In truth, it never stops; change is a constant in living systems.)

While there are significant differences in scale between the task undertaken by Kynes to terraform an entire planet and that of the British in terraforming Ascension, I think the two efforts can be realistically compared. If anything, Ascension, with its arid environment, can be

considered a microcosm, miniature, of Arrakis. In *Dune*, Kynes's plan was supposed to take several centuries to unfold, but it lacked much of the natural trial and error of succession. On Ascension, the process has taken less than a century, but with a significant amount of successional experimentation. That experimentation continues, demonstrated by the march of mesquite and prickly pear across the bare lowlands of Ascension. While likely driving some of the island's endemic species to extinction, the development of the artificial forest has made Ascension a place where people who have no right of residency under current British policy continually renew employment contracts that keep them on the island for decades. An island described by Darwin in 1839 as "not smiling with beauty, but staring with naked hideousness," was transformed by 1920s into a place, as marine biologist Alistair Hardy wrote, where the "colours are fantastic," and "sheep grazed on the slopes of grass in between patches of almost dense jungle." But both Ascension and *Dune* illustrate the dangers of creating paradise. Some of Ascension's endemic plant and animal species have been driven to extinction as a result of the changes humans have made, such as the Dune saga, where the sandworms—arguably the most important species on the planet—are driven to extinction.

Now I know why people like Steve Lynch whispered so enthusiastically about *Dune*. Herbert's vision, as epic and fantastic as it is, is grounded in ecological reality. While reading a futuristic tale of imperial intrigue, religious mysticism, and desert adventure, we can learn something about taking care of the place we call home.

DAVID M. LAWRENCE has never decided what he will do when (if) he grows up. He is a scientist who teaches geography, meteorology, oceanography, and (sometimes) biology at the college level. He is a journalist who covers everything from high school sports to international research in science and medicine. He is a SCUBA diver looking for a way to make a living on the water. When not consumed with those activities, he looks at his guitars and wonders if he's too old to become a rock god. (It would help if he could actually play.) He lives in Mechanicsville, VA, with his wife, two children, and a menagerie of creatures with legs, scales, and fins.